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Challenging Problems in Bluff Body Wakes

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Abstract

A number of outstanding questions related to the near and middle wake structure of two-dimensional, or mildly three-dimensional, bluff bodies are presented. Experiments on a bluff body with a controlled three-dimensional geometric disturbance are described and it is shown that vortex splitting is a dominant feature of the wake flow. The use of CFD to study low Reynolds number bluff body wakes is discussed. Also similarities between vortex shedding in steady flows and in planar oscillatory flows are pointed out.

1 Introduction

Bluff body flows present a wide range of challenging problems and it is quite beyond the scope of this paper to attempt to describe all of them. Although it is by no means fully proved, it may be that very far downstream the wakes of all bluff bodies asymptote to a similar form. Discovering this structure is in itself a major challenge; however, this paper is restricted to discussing outstanding questions related to the near and middle wake structures and on how these depend on the details of the body geometry. The wakes generated by bluff bodies that have a two-dimensional, or mildly three-dimensional, geometry will be considered. Strictly, two-dimensional geometries and two-dimensional flows can only exist in computer simulations since all bodies have ends and, above some critical Reynolds number, all bluff body flows generate instabilities with some spanwise wavelength. Although great care may have been taken by both the experimentalist and the computationalist there can still be discrepancies between experimental and computational results for two-dimensional bluff body flows due to the presence of three-dimensional instabilities in physical flows. Two important developments have taken place to help resolve this problem. By carefully manipulating end conditions[(1)(2)(3)] it has been shown that vortex shedding behind bluff bodies in the low Reynolds number laminar unstable regime can be forced to be parallel to the body axis (the unproven assumption being that in an experiment parallel shedding is synonymous with two-dimensional flow). Secondly, computations are beginning to be carried out to simulate three-dimensional flow around two-dimensional bluff bodies. Hence there is now the opportunity to make very detailed comparisons between experiment and computation.

It has long been known that, given two shear layers with opposite sign vorticity, viscosity plays a minor role in the development of vortex shedding. In the case of a circular cylinder, feedback between vortex generation and flow separation position undoubtedly takes place but it is not the

primary mechanism causing shedding. A descriptive model of the fluid dynamic processes at work in the vortex formation region, was introduced by Gerrard[4]. Huerre and Monkewitz[5] describe wake dynamics in terms of local and global modes related to absolute and convective instabilities and the near wake of a bluff body is identified as a region of absolute instability. It is interesting to note how robust this instability is because even a bluff body oscillated back and forth in still fluid exhibits the same type of vortex shedding behaviour. Strong vortex shedding occurs for oscillation amplitudes as small as two cylinder diameters and it is clear that the middle and far wake can play little part in this process.

Attractions of the hydrodynamic stability approach are that it provides a theoretical background and can give valuable insight into possible mechanisms for controlling bluff body flow. Control is achieved through affecting the near wake region by some passive or active means. Passive control, say by a splitter plate or by introducing bleed flow, has a direct effect on the near wake absolute instability region. Interesting possibilities exist for flow control using active means such as body oscillation or pulsed jets. However, some distinction should be made between open and closed loop active control. Most investigators have studied open loop systems where there is no feedback between the wake and the controller. Challenges abound in this area, particularly in the application of closed loop control to vortex suppression. However, research to date suggests that suppression may only be possible in a small range of Reynolds numbers slightly above the critical Reynolds number for the onset of shedding. At higher Reynolds numbers it is possible that while one mode can be suppressed another is excited. Also the three-dimensionality of vortex shedding introduces a further complication because while shedding might be attenuated at one spanwise position it could be amplified at another. The investigation of effective control strategies is an interesting challenge for computational fluid dynamicists because, compared to the difficulties facing the experimentalist, it is relatively easy to introduce active control into computer simulations.

In this paper three challenging problems will be discussed which it is hoped will throw some light on our understanding of bluff body wakes: three-dimensionality in nominally two-dimensional flows, including the effect of three-dimensional disturbances, the use of CFD to study low Reynolds number wakes and vortex shedding in oscillatory flows.

2 The Three-Dimensional Structure of Bluff Body Wakes

Gerrard[6] was one of the first to address in depth the question of the three-dimensionality of cylinder wakes. He worked across a wide range of Reynolds number and identified key three-dimensional features such as oblique shedding and looping of vortices across to the other side of the wake. In his paper he also presents a diagram which shows the phenomenon of vortex splitting or vortex dislocation. More recently, Eisenlohr and Eckelmann[2] showed that vortex splitting occurs when there are spanwise variations in the vortex shedding frequency. A vortex dislocation or split occurs at the boundary between adjacent cells and is a means by which vortices can connect with each other when their frequencies are different. One way to quantify the degree of three-dimensionality in a vortex wake is to measure the spanwise correlation length

of some fluctuating quantity related to vortex shedding. At Reynolds numbers high enough to generate a wake of turbulent vortices, measurements indicate a typical value for the correlation length of a few body diameters. However, this length cannot be predicted and the mechanisms responsible for limiting spanwise correlation are not clearly understood.

The sensitivity of bluff body flow to end conditions and the influence of aspect ratio illustrate the important role of three-dimensional effects. Figure 1 shows measurements reported by Szepessy and Bearman[7] of the variation of the root mean square value of the fluctuating lift coefficient, measured at the centre span of a circular cylinder, as a function of aspect ratio. The ends of the cylinder were terminated by end plates and the Reynolds number of the experiment was 5.1×10^4. It can be seen that as aspect ratio is reduced below about 8, C'_L increases by as much as 50%. Even with end plates there is still some three-dimensional disturbance introduced into the flow but any strong mean cross flow near the ends is eliminated. At high Reynolds numbers there are unsteady pressure gradients imposed along the span, as evidenced by vortex shedding not being in phase over large spanwise distances. The unsteady cross flows induced by these pressure gradients are suppressed near an end plate and this seems to lead to an enhancement in the mean strength of the shed vortices in this region.

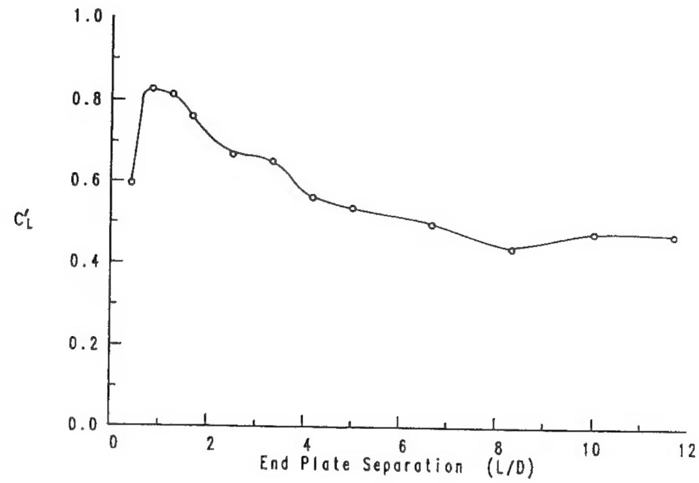
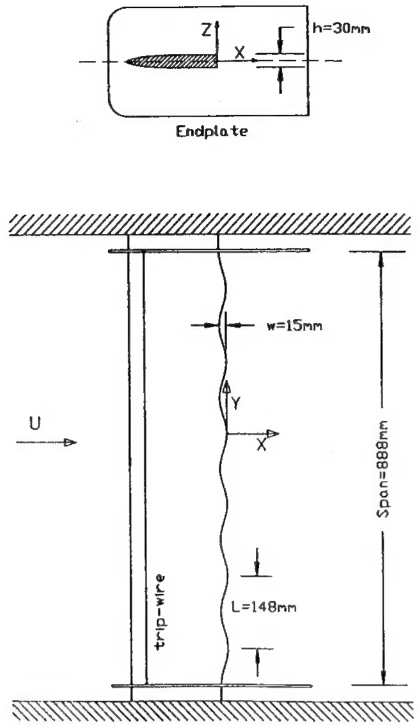


Fig 1 Variation of coefficient of fluctuating lift with aspect ratio, Re = 5.1×10^4

On large aspect ratio bluff bodies events leading to a departure from two-dimensional vortex shedding, such as a vortex dislocation, appear to occur at random points in time and space. In order to try and control these events, so that they can be studied in detail, a series of experiments has been undertaken on a bluff body with imposed three-dimensional geometric disturbances. Details of the blunt-trailing-edge body used are given in figure 2 where it can be seen that the separation points are fixed and the trailing edge is wavy. A number of different wavelengths were studied, all with a wave height equal to 25% of the base height, but most of the research was carried out on the configuration shown in figure 2. Compared to a straight edge, the



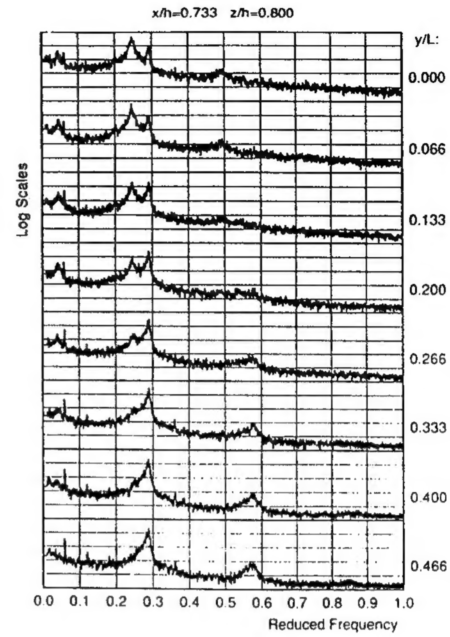


Fig.2 Geometry of three-dimensional blunt trailing edge model.

Fig.3 Variation of power spectrum of velocity, measured outside the near wake of the wavy model,with spanwise position.

introduction of a wavy trailing edge reduces base drag and the highest base suction occurs at a valley; i.e. where the chord of the model is a minimum.

Spectra of velocity signals recorded in the wake of the wavy model shown in figure 2 are plotted in figure 3. y/L=0 is a position corresponding to a peak in the waviness across the base and y/L=0.5 is a valley. It can be seen that at a valley the spectrum is centred around a single vortex shedding frequency whereas at a peak two frequencies are evident. The lower of the two frequencies is close to the shedding frequency for a straight edge and the low frequency hump rising above the background (the adjacent sharp peak is spurious) is equal to the difference between the two shedding frequencies. Using flow visualisation, two basic modes of vortex shedding have been observed around a peak in the spanwise waviness: a symmetric and an antisymmetric mode. The spectra show that the flow has to accommodate changes in the shedding frequency across the span and this is achieved via vortex splitting. A visualisation of the flow is shown in figure 4.

During the course of carrying out the above experiments an interesting additional three-dimensional effect was observed which was present on the straight-edged and the wavy models.

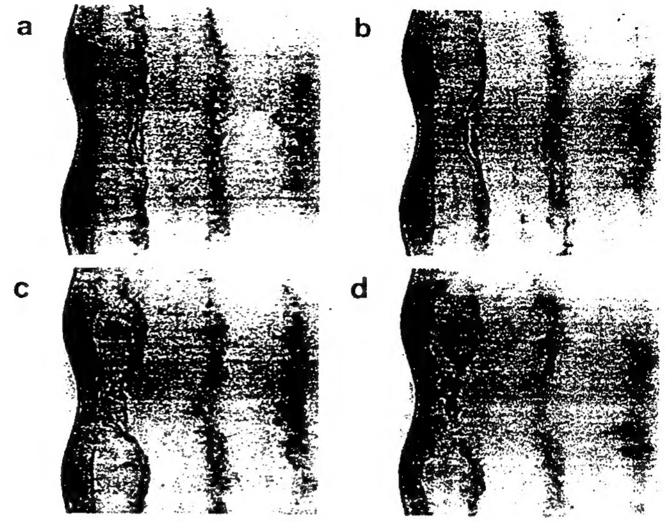


Fig.4 Visualisation showing the symmetric mode and the development of a double dislocation.

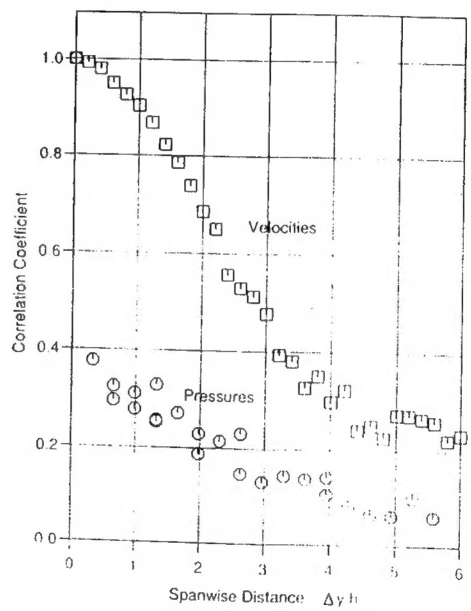


Fig.5 Measurements of correlation coefficient against
spanwise separation for a straight trailing edge model:
▯, velocity outside the near wake; (), pressure at the centre of base.

Figure 5 shows two sets of spanwise correlation measurements: one for fluctuating velocity measured just outside the near wake and the other for fluctuating base pressure. It can be seen that the base pressure correlation initially falls off very rapidly with spanwise separation, indicating strongly three-dimensional flow. Visualisation using a spanwise light sheet along the wake centre line shows a relatively small scale and apparently random vortex structure which may be turbulence entrained into the near wake or the remnants of a longitudinal vortex structure originating in the shear layers shed from the body. The remainder of the base pressure signal measured along the centre of the base is mostly at twice the shedding frequency and substantially better correlated.

3 Numerical Simulation of Bluff Body Flow

One of the most exciting aspects of numerical simulation of bluff body flow is the possibility it offers for studying in detail the mechanics of vortex formation and shedding. However, in attempting to compare computation with experiment two obvious difficulties arise. At Reynolds numbers up to about 150, where it is appropriate to carry out two-dimensional simulations, there is for good practical reasons a lack of detailed experimental measurements of mean and unsteady forces. At higher Reynolds numbers three-dimensional instabilities, both small scale and large scale, should be modelled but presently the very considerable computer resources required restrict activity in this area to just a few research groups.

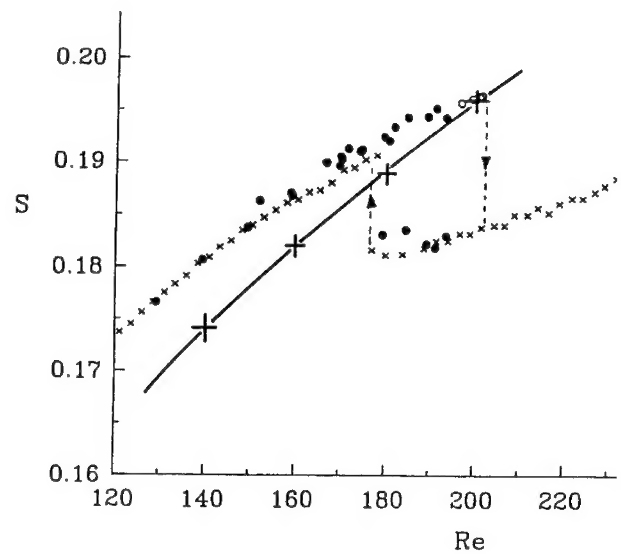


Fig.6 Strouhal number versus Reynolds number. x, Williamson[1], 0 and ●, suction end control, Williamson[9]; +, computation[8].

A paper by Meneghini and Bearman[8], to be presented at this meeting, describes the application of a two-dimensional discrete vortex code to study control of the flow around a circular cylinder. The control is applied through body oscillation and the numerical method incorporates an Eulerian vorticity diffusion scheme and a Lagrangian convection algorithm. In order to calculate the diffusion of vorticity correctly, great care has to be taken to ensure that the mesh used is sufficiently fine, particularly near the body surface. The Reynolds number of much of this work is 200 and this means that the results cannot be compared directly with experiment. However, Williamson[9] has shown that laminar flow with parallel vortex shedding can be extended to a Reynolds number of 200 if suction is applied at the edges of the wake. Measurements by Williamson of the Strouhal number for a circular cylinder are shown in figure 6 together with values obtained from the numerical method. It is clear that there is a systematic difference between the two sets of results. An obvious possibility is that there is an error in the simulation method although the present results agree well with those of Braza et al[10] who used a different numerical scheme. Alternatively is there some hidden three-dimensional effect in the experiment which is responsible for the differences?

4 Vortex Shedding in Oscillatory Flow

The flow around a cylinder undergoing relative sinusoidal motion along a diameter is a function of the Keulegan Carpenter KC and the Reynolds number Re. KC = UT/D, where U is the maximum velocity during a cycle, T is the period and D the cylinder diameter. Re is formed using U and D. An alternative viscous parameter is β, where β = Re/KC = $D^2/\nu T$. The configuration of vortex shedding is primarily a function of KC and the various patterns have been described by Bearman[11], Williamson[12], Obasaju et al[13] and Tatsuno and Bearman[14]. If the oscillatory flow is from side to side then, above a KC value of about 6 or 7, vortices form alternately from the upper and lower sides of the cylinder. As KC is increased by an increment of about 8, another fully formed vortex is shed in each half cycle. The mechanism by which vortices are convected from the cylinder is through mutual induction whereby a pair of vortices of opposite sign induce a velocity on each other. By the end of a cycle a vortex may not be fully formed and it will remain to influence shedding in the next half cycle. If it is sufficiently strong it will pass back over the same side of the cylinder as the one on which it was formed. This will help to accelerate the formation of an opposite sign vortex in the shear layer that forms from that side at the beginning of the next half cycle. If the vortex is weak it will pass around the cylinder and find its way into the similar sign vortex forming in the diametrically opposite shear layer in the next half cycle.

At high KC values, say in excess of 40 or 50, the cylinder might be expected to shed part of a vortex street in each half cycle. Bearman et al[15] have devised a simple quasi-steady model of vortex shedding to predict the fluctuating transverse or lift force on a cylinder in oscillatory flow. Since the magnitude of this force is expected to depend on the square of velocity, the oscillating flow will induce an amplitude modulation on the lift. Assuming a constant Strouhal number then in oscillating flow the fluctuating lift will also be frequency modulated following the variations in velocity. A fit of the model equation to experimental data for a circular cylinder

is shown in figure 7. The interesting point about this approach is that the best fit is obtained when the Strouhal number takes its steady flow value of 0.2.

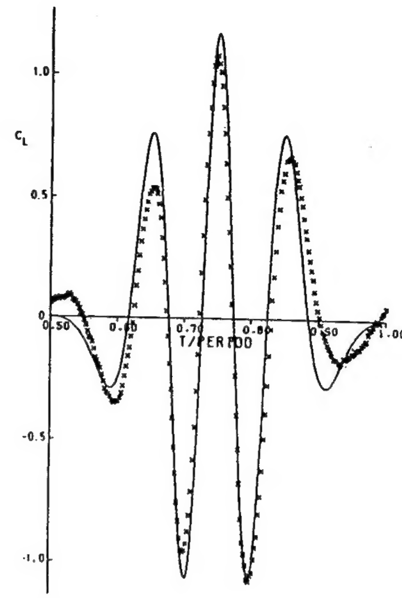


Fig.7 Coefficient of transverse force on a circular cylinder in oscillatory flow.
x, experimental data; —— quasi-steady model with S=0.2[15].

5 Outstanding Questions

Instead of attempting to present a series of conclusions to the work outlined above a number of questions are listed. These are offered in no particular order of importance.

(a) What determines the degree of spanwise correlation of bluff body flow?

(b) Are vortex dislocations a fundamental feature of high Reynolds number bluff body wakes?

(c) What new insights into bluff body wakes can be obtained from new experimental techniques that provide instantaneous spatial information, such as particle image velocimetry?

(d) What can be learnt about bluff body flows by applying passive or active control and is it possible to use active control to suppress vortex shedding at high Reynolds numbers?

(e) In the lock-in region what determines the phase between body or incident flow oscillations and vortex shedding?

(f) What can further study of low order dynamical systems offer towards the understanding of bluff body wakes?

(g) What is the future role for hydrodynamic stability theory in the study of bluff body wakes?

(h) Is there any need for more experiments at low Reynolds numbers with parallel shedding or can CFD simulate these flows adequately?

(i) What problems should researchers working on three-dimensional simulation be trying to solve?

(j) Can what has been learnt about vortex shedding in steady incident flows be applied in oscillatory flows?

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